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Recommendation of RILEM TC 243-SGM: Functional Requirements for Surface Repair Mortars for Historic Buildings

Jan Válek[1*], John J. Hughes[2], Francesca Pique[3], Davide Gulotta[4], Rob van Hees[5], Ioanna Papayiani[6]

[1] Czech Acad Sci, Inst Theoret & App Mech, Czech Republic
[2] University of the West of Scotland, Paisley, Scotland
[3] SUPSI, Lugano, Switzerland
[4] Department of Chemistry, Materials and Chemical Engineering “Giulio Natta”, Politecnico di Milano and INSTM, Italy
[5] TNO, Delft & TU Delft, Netherlands
[6] Aristoteles University of Thessaloniki, Thessaloniki, Greece

* Corresponding author, Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences, Prosecka 76/809, Prague, Czech Republic, +420 283 880 458, valek@itam.cas.cz

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Chairman: Caspar Groot, The Netherlands
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Members: Beril Bicer-Simsir, USA; Luigia Binda, Italy; Christine Bläuer, Switzerland; Violeta Bokan-Bosiljkov, Slovenia; Davide Gulotta, Italy; Rob van Hees, The Netherlands; John Hughes, Scotland; Albert Jornet, Switzerland; Ioanna Papayianni, Greece; Vasiliki Pachta, Greece; Francesca Piqué, Switzerland; Stefan Simon, Germany; Zuzana Slížková, Czech Republic; Maria Stefanidou, Greece; Cristina Tedeschi, Italy; Lucia Toniolo, Italy; Rosario Veiga, Portugal.

Abstract
Surface repair mortars are used for the compensation, or repair, of lost portions of surface materials in historic masonry buildings. It is recommended that their design and application should be performed in a wider context of conservation values related decision making, to prioritise preservation of original fabric, authenticity of approach and maintenance of integrity, and not just on technical principles alone. However, a technical context for their design does exist, that requires understanding of the properties of the substrate that they will be applied onto, and adherence to minimum aesthetic (colour and texture) requirements. The principles of physical, mechanical and chemical compatibility of repair apply and the attributes of the repair mortar should be carefully matched to the substrate alongside a sacrificial behaviour (not more durable than the material being replaced). Guidance is given on the design, application and the functional requirements that must be met when using surface repair mortars.

Keywords: surface repair, mortar, historic masonry, functional requirements

1 Introduction

This document deals with mortars used for the repair of historic stone and brick substrates. Various terms, referring to the same or very similar interventions of surface repair are in use,

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such as *mortar repair, plastic repair, surface fill, loss compensation mortar repair, stone imitation, stone patch* [**1, 2, 3, 4**]. What these repair methods have in common is that a missing part of an original material is replaced by using a new material which is pliable when applied and therefore can be adapted into various shapes and finished with the required surface texture. These actions are usually carried out on a small scale, modelling each individual architectural element (stone block or brick) separately or the missing part of sculpted and/or decorative elements in order to restore the original integrity. This individual approach (modelling an architectural or sculptural element or detail) is the main difference from other repair actions with the use of mortar.

The terms *surface repair mortar* and *mortar repair* are preferred in this document because they correspond to its scope that focuses on the use of mortars to repair missing parts of facades, architectural and sculptured decorative elements and archaeological remains made of various materials (mainly natural and artificial stone). It deals with visible repairs whose function is principally aesthetic and preventive. Mortar repairs that significantly contribute to load distribution within the structural elements are out of the scope of this paper. In addition to the enhanced aesthetic appreciation of architectural elements by maintaining their integrity and continuity, the *mortar repair* contributes to the protection of the original material that it covers (thus preserving historic material value) and in this way reduces the effects of deterioration processes that can be promoted by the presence of voids and discontinuities of the surface due to loss of material.

In the conservation community the wish that treatments should be both durable and reversible is often expressed. Under most circumstances this is a contradiction in terms and the aspect of reversibility is mostly considered in terms of “re-moveability” mainly by mechanical action. Other approaches for organic binders can involve the use of solvents but are not covered in the present article [4, 5].

The main aim of this document is to summarise and review the current expertise in the application of surface repair mortars in order to provide some practical guidance for their design for stone and brick substrates. The review stems from other publications related to this topic that were already published by RILEM TC 203 RHM [**6**, **7, 8, 9**].

2 Preliminary considerations

2.1 Current situation and experience

The idea of using various binders and mortars for imitation of stone can be traced back to ancient times. It has developed through the centuries up to the present day reflecting technical and architectural progress. Increasing interest in the conservation of historic buildings, an appreciation of exposed stone facades and the increasing availability of cement and other new binders and additives also led to the widespread use of mortar repairs for stone in the 20th century. Mortar repairs range from just a simple filling of holes with almost any kind of mortar to a highly specialised conservation treatment, such as described in [**1**] and to an increasing number of *ready-made* repair mortars available from industry. Mortar repairs of various qualities are currently found on many historic buildings. This raises questions about the appropriateness of such repairs, their functionality and durability. Objections to the use of cement-based mortars in repairs of cultural heritage buildings due to their incompatibility with traditional building materials, are well known. However, a recent study showed that over 50% of surveyed buildings in Glasgow, Scotland, had some form of a mortar repair containing cement

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[**10**]. Fig. 1 shows the deterioration of an exposed sandstone façade; Fig. 2 shows an application of mortar to repair individual stone surfaces on a building in Glasgow.

The evaluation of the performance of mortar repairs carried out in the past can provide information about the overall compatibility and durability, in order to improve their future use. Appearance and architectural quality can often be judged by visual observation. In some cases, the mortar repair appears to be performing as required, as illustrated by Fig. 3. However, there are also less successful cases as presented in Fig. 4. In this latter case, the deterioration of the stone units has continued and after several years the stone surface recessed whilst the more durable mortar repair patches remained at the original level. In this example the contrast between the colours and textures of mortar and stone is also notable. Such a situation is today aesthetically unacceptable, and the profile difference causes accelerated weathering of the stone around the edges of the protruding repair by trapping water or by wind erosion and eddies. Experience from building surveying suggests that the longevity of well executed mortar repairs is about 30 years [**11**]. This potentially limited life span must be taken into account in the repair design stage and in the requirements for post treatment monitoring and maintenance. Failure of the mortar may also occur as a result of mechanical and/or aesthetic incompatibility. In particular, the addition of synthetic resins in the past has led to unsuccessful repairs due to remarkable colour alteration and to very different mechanical properties between the mortars and the stone substrate (Figs. 5 and 6).

2.2 Design of mortar repair

First of all, it is important to preliminarily assess whether or not the use of repair mortar would be the optimal conservation action to be undertaken. This decision is often based on a complex repair strategy and on some monuments it can be forbidden by a general conservation policy. However, each case has to be considered individually. Repair actions such as stone replacement (by natural stone), various types of coatings (protective, sacrificial), material consolidation or even no action are often considered as alternative possibilities. It should be recognised that the mortar repair technique is often more complex than a simple filling of holes including also treatment of the substrate (e.g. removal of material, consolidation), use of reinforcements and surface finishing techniques.

The significant decision-making factors when considering mortar repairs as a possible conservation strategy are the following:

- Preservation of as much as possible original material if compared with (stone) replacement.
- Impact on surrounding fragile areas of original material.
- Avoidance of removal of structural elements (i.e. compare mortar repair with the replacement of whole masonry unit).
- Exposition conditions.
- Sacrificial performance of surface mortar can be considered and designed.
- Size of areas to be repaired.
- Visual appearance of mortar repair versus (stone or brick) replacement.
- Availability of skills and knowledge to carry out a high quality repair.
- Availability of natural stone possibly from the same quarry as the authentic original stone (in preference to mortar repair).

The initial preparatory work to be undertaken is the following:

- A standard building survey should be carried out; i.e. proper documentation of the state of original material prior to the repair actions, understanding of architectural and construction details, construction and material interactions and previous conservation actions.
- Material characterisation with specification of its properties, texture, finishes and coatings.
- Condition assessment. Causes of material deterioration should be determined and any conservation action to reduce the risk of future deterioration should be addressed. Condition of the material should be evaluated considering it as a potential future substrate for the mortar surface repair.
- Evaluation of the overall exposure conditions, with respect to the main climatic parameters and also pollutants.
- Specification of individual requirements for each single case (type of substrate, like masonry unit, architectural detail, part of sculpture and specific conditions like exposure to rain, presence of salts, …).

A suitable, long lasting mortar repair should be designed considering several requirements. The *conservation issues* should be always considered first to define the general approach from the philosophical, ethical and conceptual point of view as recommended by RILEM TC-167COM [**12**]. These issues are always linked to *architectural appearance* and appreciation of historic buildings and their fabric. The appearance, colour and texture of mortar repairs is therefore often of a paramount importance. All this has clear consequences for the selection of the type of binder (and repair mortar composition) and on the formulation of the technical requirements on mortars and the whole repair procedure.

Concerning the specific technical requirements, they should always be based on analysis of the substrate regarding aesthetic (e.g. colour, texture, finishing technique), compositional, mechanical and physical parameters as stated in the list above. Based on this complex knowledge, key functional requirements can be established that will need to be fulfilled by the new mortar repair. The following sections consider these issues, of preliminary assessment and specification, in more detail.

2.3 Conservation issues

Mortar repair carried out on the fabric of historic buildings is considered a conservation-restoration treatment, because a new material and modern techniques are applied. It is a repair action that has to be technically designed taking into account conservation principles and requirements. Such design has always to start from the general approach and conceptual requirements [**12**] that can be derived from the international cultural heritage charters [**13**] as follows:

- There should be no conjectural repairs.
- The efficiency or adequateness of materials and techniques used for repair should be supported by scientific data and/or by field experience.
- Replacement of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original (i.e. there should be no falsification of the artistic or historic evidence).

The average longevity of mortar repairs, previously stated, should raise questions and additional considerations about:

- The availability of repair materials and the current ability to make a correct choice that needs to be matched with the right application skills.
- The *repeatability* of the treatment; the potential loss of original material due to inefficiency of the mortar repair should be evaluated in advance.
- The appearance and appropriateness of such repair upon weathering after the application.
- The requirements for long term monitoring and maintenance.

In addition to this, the mortar repair should be compatible with the historic fabric. This compatibility requirement is applied in building conservation theory and practice to prevent direct or indirect damage to the original material and to ensure the long term stability of the intervention. The technical definition of material compatibility of repair mortars with the original material requires that no damage should be allowed to the original material within the service life of the repair [**14**]. The specification of a repair mortar from the technical compatibility point of view is based on the comparison of properties of the new mortar and the original material. A variety of important characteristics to be compared have been suggested in literature [**15, 16**] and the compatibility concept has been reviewed by Hughes and Válek [**17**]. The compatibility requirement is one of the main factors to be considered when a mortar repair is proposed and assessed.

Good adhesion (bond) between the substrate and the repair mortar is commonly presented as one of the main measures of success of repair and its long term durability. However, this is also where two different materials have to perform together, both exposed to the same environmental stress, but with potentially different responses to these factors, for example, differential thermal expansion, differences in water and water vapour transports. Having the bond strength higher than the tensile strength of the substrate is not desirable in the case of historic structures [**18**]. To fulfil the cultural heritage protection requirements the potential failure should not occur in the original material, but in the mortar repair or at the interface between the mortar repair and the original, when the bond is tested. When assessing the compatibility criteria, it is important to consider that the mechanical and physical properties of the weathered substrate can be significantly lower that the sound material. Also increased moisture content can cause lower strength of some natural stones (e.g. sandstones). In addition, the determination of mechanical properties of historic materials is a challenging task and often innovative and non-standard methods need to be employed [**19**]. This is particularly significant where destructive sampling for off-site testing is not permitted, as is mostly the case for historic structures. Non-destructive tests need be employed where possible in these cases, however the calibration of values obtained from these tests with values normally required in specifications is often imprecise and therefore difficult to interpret.

2.4 Appearance and architectural issues

Mortar repair is a visible surface repair and its appearance is very important from architectural, conservational and material points of view. The view on how the mortar repair should be visible and distinguishable, also known as the “honesty” of the repair can vary. However, general guidance is suggested in Table 1 and the following figures.

2.5 Assessment of substrate

Characterisation of the main compositional, mechanical and microstructural features of the substrate aids in understanding the current state of the conservation of the materials and their construction. In addition, the results of characterisation are relevant for the assessment of compatibility between the substrate and the repair mortar. The most relevant properties have to be identified based on the contingencies of individual cases, and also depend on the possibility to take samples for laboratory testing and the use of other in-situ tests. Non-destructive tests (NDT) are preferred whenever possible, although a multi-analytical approach also supported by laboratory diagnostics generally provides a sounder characterisation background.

The aim is typically to assess the soundness of the material by identification of strength properties. Also the deformation behaviour of materials under loading is a key parameter (i.e. elastic modulus), though its determination is not easily achievable. Instead, ultrasound NDT tests can be also used for a comparative assessment on samples in the laboratory or in-situ. Ultrasound propagation through materials can be related with some accuracy to dynamic modulus of elasticity. For porous building materials very important properties are always those related to moisture transport mechanisms. This means open porosity, capillary absorption, water vapour permeability and pore size distribution. Samples are also often taken to characterise material composition and the presence of water soluble salts. An additional important factor to consider is the representativeness of the determined properties and analyses including understanding of the natural variety of stone properties and the effects of weathering and degradation.

2.6 Binding agents

Distinguishing among repair mortars by the nature of the binding system is practical as it predefines the preparation, application, curing and final performance of the repair mortars. It is therefore quite relevant at the initial stage of the design of repair to be aware of available mortars and their binders. The basic guidelines on the *relative* performance properties of different binding agents is shown in Table 2 (according to [**6**, **7**]). The most widespread repair mortars are based on inorganic mineral binders such as cement, lime-pozzolana and natural hydraulic lime or lime binding systems. Such binders are common in ready-made proprietary mortars but they can also be used in customised, bespoke design. Their advantage is availability and the long term and widespread experience with their use in building practice. New binders have been recently developed and used for stone repair, such as the silica based TEOS and dispersed colloidal silica. Organic polymers are known and have also been successfully used as binders [**2**]. The most commonly known organic polymer binders are epoxies and acrylics. Epoxy based mortars have typically been used to imitate sandstones (e.g. Linostone [**20**]). Experience with the epoxy mortar replicas of sandstone sculptures after forty years of exposure shows that the main cause of failure is an improper compliance with prescribed preparation and application technology due to their strict demands [**21**]. Both epoxy and acrylic based mortars are known for their differential behaviour from natural stone when exposed to outdoor climatic conditions [**1**], see also Fig. 6. Another class of binder can be classified as 'chemical' [**3**] for example zinc hydroxychloride mortar from Belgium [**22**]. Such geopolymers are finding increased application and have been successfully used for replication of smaller stone objects. They can theoretically be used to fill voids and cavities [**23]**. However, their application in historic buildings is still a matter of development. Their main disadvantages are a complicated preparation and a high content of alkaline salts. Similarly, the modified mixed type binders, for example epoxy modified lime-pozzolan systems, are known but their use on protected historic buildings is not common.

3 Design and application issues

The mortar mix can be *custom designed* or be *ready-made proprietary.* There are some advantages and disadvantages of both types that need to be considered. Other considerations relate to the substrate and application procedures.

3.1 Custom design of mortars

Custom designed mortars can possibly be the most appropriate in matching required properties. Most commonly, custom-designed mortars are based on lime, lime-pozzolana, natural hydraulic lime, cement or natural cement binders as these binders are well known by all relevant professionals involved in the stone repair process. An advantage of custom design is the possibility to tailor the mixture in order to meet specific requirements. For example, those properties related to porosity and water transport mechanisms. However, such an approach requires a great professional experience and technical knowledge, the support of laboratory tests and their verification. It is an overall rather costly and time-consuming approach and therefore it may not be realistically achievable in all cases.

The selection of the individual mortar components depends on both aesthetic criteria (the type, colour and texture of the material to be reinstated) but also on the mechanical and physical properties (such as strength, elasticity, porosity and coefficient of thermal dilatation) in order to make sure that the repair materials will be functional. The final visual appearance imitating or matching the substrate is in many cases the paramount criterion. The selection of binder (the binding system) is a starting point of the mix design as it predetermines the physical and mechanical properties of the mortar mix as well as the capacity of the mix to be adapted to the appropriate form and appearance. Aggregate and additives, however, can significantly modify the properties of mortar.

Standards (EN, ASTM, BS etc.) specifying individual components for mortars and concretes are available. They may not exactly apply to this specific type of application but should be referred to in general for characterisation of the individual components.

3.1.1 Binder

Custom design typically uses mineral binders known also from other mortar applications, i.e. cements and limes (air, natural and lime-pozzolanic). Reactive pozzolanic additives (e.g. brick dust, metakaolin, microsilica, volcanic ashes) are part of the binding system [**24**]. They contribute to the hydraulicity of lime-based mortars, modify porosity of the binding system and limit lime leaching.

Selection of the appropriate binder should allow the matching to the specific properties identified by the analysis of the substrate. This includes physical properties like porosity but also other factors ensuring that the new mortar is compatible with the substrate as well as durable. Special attention should be paid to the appearance of the final material. Lime rich mortar mixes may not be suitable for matching some sandstones and the use of grey cement suppresses colour shades.

3.1.2 Aggregate

Aggregate is selected and designed according to the required colour and texture. This is constrained by first analysing the original material and choosing an aggregate that matches it in appearance and grading. In principle, aggregate constitutes the major part of mortar, reduces shrinkage, affects workability and fresh properties, modifies mechanical (compressive strength) and physical properties (porosity and pore size distribution) including visual appearance (colour and surface texture). The gradation, size and shape influences the amount of water used for mixing and in general the mortar workability. Aggregate used for a surface repair mortar is often composed of several fractions of various sands and crushed rocks. The shape, size and colour of grains should also match the material that is being reinstated. Natural aggregate should be preferred. If possible, the original material can be crushed and used as filler in order to improve aesthetic compatibility [**25**]. Aggregate should be resistant to an alkaline environment and should be adequately durable. Apart from the natural sources, other aggregates can be used mainly to achieve a specific appearance, e.g. glass microspheres, solid resins, recycled aggregates (from reprocessed construction materials) and other materials.

A special category are pozzolans. They could also be considered as a part of the binding system, however, they also act as very fine filler (especially the natural pozzolans). Pozzolans generally reduces alkali reactions with aggregate and other additives. Pozzolans may also be used to influence the colour of mortar, e.g. use of coloured metakaolin, brick dust etc.

The mixture of various aggregate fractions should be well designed and tested to understand the effect on porosity and its pore size distribution and water and water vapour transport related parameters. Homogeneous distribution into the mixture is necessary and proportions of materials (the mix ratio) should be decided after trial mixtures.

3.1.3 Additives (Admixtures)

Additives are added to a mortar mix in small proportions to influence the properties of fresh or hardened mortar, or both. Additives have been used historically in mortars and a variety of modern chemical products are available. The effect of additives on mortar must be known or assessed before their application. Air entraining agents are often recommended in cement based binding systems to improve frost resistance. Pigments are added to adjust the colour of mortar. To be effective, in common with aggregates, pigments should be resistant to the alkaline environment and should not fade or alter upon exposure to solar radiation outdoors (e.g. are resistant to UV light). Fibres, microfibers, natural or manufactured, are used for reduction of shrinkage and to improve the integrity of mortar. Water repellents are used to limit capillary absorption from the outer sources.

3.2 Ready-made proprietary mortars

The use of available *ready-made proprietary* mortars is common and a practical solution applied in many projects. A variety of international and national companies offer pre-mixed restoration mortars that can be used for mortar repair. Some products are universal, others are designed to match a certain type of natural rock or material. Local products can even be developed to match regionally specific rock composition and climatic conditions. Companies specialising in these products sometimes offer custom adjustments to match the colour or the grain size. The advantage of these products lies in their consistent composition within the same batch, well graded aggregate, though rather fine in size, appropriate gauging of pigments and easy to follow instructions often including advice on the use of other products to improve the bond, attachment of reinforcement or to help with the surface finishing. Companies producing some of these highly specialised products also provide training and issue certificates to ensure appropriate application. A potential advantage for the customer is also the possibility to assess their previous applications.

Most proprietary stone repair mortars are based on mineral binders that are some type of cement. The disadvantage of these mixes lies in a lack of information about the actual nature of the components (especially as far as the precise type of binder and the presence of possible admixtures are concerned) and also the inability to modify them. Their individual properties cannot be adjusted to specific requirements. They are designed to fulfil the most common requirements and this “non-specific” range of application approach can be in some cases quite a limiting factor. It is also worth noting that modifications of the mixtures due to variations in the production process can occur, leading to differences in the final performances of mortars prepared with different batches. Table 3 presents a selection of commercial products available on the market, illustrating their performance parameters. Generally, not all material properties are stated by the producer in the technical data sheet and may need to be requested from the producer; often important properties like shrinkage, thermal expansion, drying behaviour are missing. The manufacture typically only provides data that help to determine the product’s suitability from a specific point of view and the properties are not guaranteed. Relevant parameters have to be selected and determined by the user to assess the suitability and compatibility of the product considering all associated risks. A possible approach for very important historic monuments is to undertake a comparative study of various mortar mixes including own custom designed and commercial ones [**26**].

3.3 Preliminary operations on the substrate

The stone to be repaired should display adequate mechanical properties, in particular cohesion. Depending on, and according to the cultural value attributed to the structure, powdering parts can be removed by mechanical actions (cutting) and/or be consolidated [**37, 38**]. Practical advice can be found in conservation literature [**1**]. Care should be taken not to weaken the stone by cutting. A minimum depth of approximately 20 mm for the repair is required and the edges should not feather out. They should be slightly undercut apart from the bottom edge, which is recommended to be cut straight. For masonry units a rectangular shape with the edges parallel to the joints is recommended. The repair area must be cleaned of stone dust and any other substances, which may prevent proper adhesion. There may be increased requirements on bond when a greater amount of material is reinstated by mortar and/or when there is danger that the repaired part may fall down if not properly bonded (safety aspects). Also the repaired unit has to be firmly embedded within the structure so it will be able to carry the additional load added by the repair.

3.4 Reinforcement

The bond between the surface repair mortar and substrate can be provided by reinforcement pins using non-corroding materials that are anchored in the substrate (Fig. 9). In this case the reinforcement carries the loads between the substrate and repair, and acts together as a system. The type of reinforcement can vary from simple wires to complex meshes. Stainless steel and/or non-corroding materials, such as nylon of fibre-reinforced composites, should be used. Reinforcement should be set back from the mortar’s surface, typically a minimum of 10 mm or at least twice the diameter of the reinforcement in order not to become exposed when the mortar weathers. Setting back also helps in avoiding problems associated with thermal expansion of the reinforcement. Wires need to be embedded into the stone for the depth of at least as much as the depth of the cavity being filled and fixed into the stone with some adhesives (usually epoxy resin or cement mortar-grouts, (Fig. 9).

3.5 Mortar mixing procedures and fresh mortar properties

Basic principles of mortar mixing apply also for surface repair mortars. Proprietary ready-mixed mortars need to be prepared according to their specific instructions. Custom designed mortars can be mixed on site. If possible, it is better to have the mortar ingredients pre-mixed dry so that only water has to be added. The mortar ingredients should be carefully measured by mass. The moisture content of the aggregate should be taken into account if mixed on site. Small amounts, which are typically the case of the surface repair mortars, can be mixed by hand or by a drill with low speed (400-600 rpm). The water amount can vary depending on the required workability. The resulting mortar should be homogeneously mixed and workable according to the specific application. A well-organized site is of importance and continuous supervision is necessary in all stages to ensure reproducibility of the mixing procedures (and of application).

3.6 Application procedures, curing and protection

Also for application, curing and protection, the basic masonry practice principles apply. The mortar is applied to the pre-wetted and previously prepared area to be repaired. It has been a common practice that a special thin layer of diluted mortar mixture or binder is applied before the application of the mortar. This aims to prime the surface and improve adhesion (also known in practice as an Adhesion Bridge). The repair mortar is then applied directly on the wet layer in well pressed and compacted layers around 10–20 mm thick and usually no thicker than 30 mm in order to reduce the shrinkage and improve the compaction of mortar. Thickness of a layer depends on the consistency of mortar and relates to the size of aggregate and filler particles. Where several layers are applied usually the same binding system is used. The aggregate can be adapted and coarser sand can be used for deeper layers. It is advisable for all layers to be of similar colour to the surrounding material. Application of subsequent layers of wet on wet is most commonly preferred. Each layer is allowed to have an initial set. The surface of the repair is pressed, scratched and rewetted before another layer is applied. The final layer is built beyond the surface of the original material and after reaching the initial set it is scraped away and tooled to obtain the required texture. Some commercial solutions prescribe specific procedures regarding the layers, their thickness and timing between their subsequent applications.

Ambient and substrate temperature must not be lower than 5°C or above 30 °C and the work should be planned to avoid frost damage.

Curing depends on the type of binder but in any case rapid drying must be avoided. The surface can be wetted by spraying clean water in regular intervals according to the weather conditions for approximately 2–3 days. For hydraulic binders, damp-curing can be achieved by installing a wet burlap fabric covered by a plastic sheeting onto the masonry with regular re-wetting of the burlap before it dries. Direct sun, wind or rain must be avoided if possible for a period at least 7 days. This applies especially for aerial/natural hydraulic mortars characterised by slow hardening processes.

3.7 Finishing techniques and coatings

The appearance of the mortar is related to the approach adopted for the restoration. Several finishing techniques can be applied using different tools imitating stone surfaces and their textures e.g. broached, polished, washed etc. (Fig. 10).

The colouring can be integral, through the whole mortar layer, which is usually recommended for a long lasting repair. However, in many cases the colour of the last mortar layer is only of a similar shade and the fine finishing is done by retouching, using pigments bound by a stone consolidant. The exterior surface (the outer 5 mm) of the repair can be applied at a later stage to obtain the aesthetic requirements. So the core of the repair has to provide good adhesion

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and chemical and physical behaviour, but the surface can be improved later with an addition. This is common practice for epoxy-based repairs, which must be protected from sunlight. Masonry finishing, cutting and grinding is also possible on some mortar repairs after they obtain at least 80 % of their strength. For the cement based mortars this would be typically after 28 days.

3.8 Quality control

The mortar repair is often carried out in small amounts. Therefore, it is possible to pay attention to precise gauging of mortar ingredients and mixing etc. Workmanship, experience and skills are the important factors for the successful work and account to a great extent for the long term stability of the repair. Small trial panels should be carried out when a new mortar mix and repair procedure is proposed. All the mortar’s features, namely composition, mixing procedures, application conditions, curing, colour and surface final finishing have to be designed in advance and kept constant throughout the repair period.

3.9 Maintenance plans and consideration of long term durability

Long term performance of the repair should be considered during the design of the repair intervention. Recommendations of regular visual inspection for the early detection of any alternation/deterioration pattern should be provided. The mortar design and application procedure should be recorded for future reference, along with the other documentation of the repair action.

4 Functional requirements

The technical design of a mortar repair has to deal with a number of functional requirements. Their correct specification should ensure quality, compatibility and durability of the repair. It is essential to link or express them as material parameters or measurable values, whenever it is possible, as in this way they effectively serve as quality control or compatibility assessment parameters. The following sections describe the most important requirements that should be addressed when designing a surface repair mortar.

4.1 Aesthetics

4.1.1 Appropriate colour and texture

The colour and final finish (texture) depends on the composition of the mortars used for the repair and on the application method. The appearance is a very important part of the design and it influences also the choice of binder, filler and additives. If the original material is being matched the best way is to carry out several trial panels with a variety of mortar designs and surface finishes. Appropriate colour and texture should be selected based on trial panels. The application method and degree of setting before the final finishing can also influence the final appearance, thus consistency in the procedure has to be maintained once the appropriate colour and surface finish is selected. Integral colouring is preferred over thin painting layers, which may quickly deteriorate when exposed to the environment and reveal the layers underneath. The ingredients in the mortar which influence the colour (pigments) should be stable in the alkaline environment.

4.1.2 Weathering and deterioration should be similar to the adjacent materials (e.g. stone)

When mortar repair is used to fill cavities in a relatively soft material it should be expected that the original material will continue to deteriorate and the new repair mortar should ideally deteriorate at a similar rate. Mortar repairs that are more durable than the substrate will become unacceptable in the future due to their appearance but also due to the fact that the protruding parts can trap moisture and accelerate decay of the substrate along the interface.

4.1.3 No mortar staining resulting from the application

No stains from the surface repair application are acceptable on historic fabric. Protecting tapes and other measures should be taken to avoid staining during the application.

4.1.4 Low risk of lime leaching

Proper selection of raw materials can deter the danger of leaching. The masonry and mortar should not be exposed to excessive moisture absorption until the mortar is hardened. Proper curing, appropriate time of application before freezing weather should minimise the risk of lime leaching out of repair mortars. In the case of lime-based binders, any uncarbonated calcium hydroxide can be transported to the surface and can cause whitening of the surface. In the case of permanently wet conditions, calcium carbonate can be dissolved and cause lime leaching stains too. Similarly, cement-based binders contain free calcium hydroxide that is released by the hydration reaction that can leach out on the surface. Addition of pozzolans can be used to reduce the risk of lime leaching.

4.2 Compatibility with the substrate – no damage to substrate as a prerequisite

The physical and mechanical compatibility of a new surface repair mortar with the substrate is crucial because they usually completely cover some area. The new mortar therefore should not adversely contrast in permeability and water transport properties compared to the substrate. It should also have a good bond with the substrate (concerning the properties of shrinkage, bond, tensile and flexural strength), and it should have comparable values of elastic modulus, thermal and moisture expansion coefficients [**39**]. See also Figs. 11 and 12.

These performance properties may be difficult to achieve as in many instances the visual appearance of the repair is the main factor, which dictates the type of binder and filler. For example, the use of cement based mortars for sandstone repairs, which is so often cited in literature as an example of incompatible material for their strength and low permeability, often derives from a lack of knowledge or experience in the use of alternative binder systems. The point made here is not that cement is incompatible *per se*, but that the choice of binder system needs to be made with compatibility to the substrate clearly as the main concern.

4.2.1 Similar drying rate to the substrate (or higher)

The repair mortar should allow moisture to evaporate at a similar rate as in the substrate, or higher, as in principle enhanced drying rate is preferred. Retarding evaporation could cause damage related to frost action. Alternatively, fast evaporation can cause some damage of the substrate if water soluble salts are present. This applies especially to relatively thin layers (15–20 mm) of the repair material where the salt solution is not transported to the surface of the mortar but crystallises in the substrate or at the interface between the mortar and the substrate causing delamination, disruption and detachment of the repair and/or the original. The depth, geometry and exposure of the repair should be also considered as they all influences the presence of moisture. Moisture penetrating via rainfall (driving rain) should be encouraged to evaporate and other properties related to moisture transport should be controlled by the mix design (e.g. the pore size distribution and the capillarity coefficient). The surface finish also plays a very important role in the moisture ingress [**40**]. If the substrate is permanently moist the factors to be considered are more complex but drying should be promoted. Properties related to moisture transport in porous building materials that are commonly evaluated are free and capillary absorption, total open porosity, drying rate and water vapour permeability. While considering the above mentioned complexity the general rule is that the coefficient of capillary absorption, drying rate and water vapour permeability of the repair mortar should be equal to or higher than these parameters of the substrate.

4.2.2 Need to resist moisture ingress - low risk of early age crack development. Low shrinkage.

Shrinkage of the repair mortar should be avoided or, at least, reduced. This can be done by the design and the careful selection of the aggregate. A sand mixture with a good continuous grading is preferable. An appropriate sand and a balanced binder to aggregate ratio should ensure good workability with no excessive water added for easier mixing. The design has to optimise this to keep the added water to a minimum. Another factor is the correct application procedure. Mortar is applied in subsequent layers and is well compacted and appropriately cured. No rapid drying should be allowed, i.e. the work should be protected against direct sun, high ambient temperatures, and humidity and wind conditions should be also taken into account. Drying also occurs through the suction of the substrate, so appropriate pre-wetting of the substrate and each application layer is essential. Through assessment by selective testing, mortars with low shrinkage and appropriate performance parameters should be preferred. Although aiming at the minimisation of shrinkage, caution should be paid to an unwanted increase of strength of highly compacted mortars made of hydraulic binders with low w/c ratio. An alternative solution for cement based mortars is the use of shrinkage reducing admixtures that are well known in industrial mortars and their use in conservation could be examine as a solution in the future.

4.2.3 Similar thermal and moisture expansion properties compared to the substrate

Typically traditional building materials have a coefficient of thermal expansion between 6 to 18.10^{-6} K^{-1} [**41**]. A similar thermal coefficient (i.e. ± 2. 10^{-6} K^{-1}) of the repair mortar and the substrate should not induce stresses exceeding the load bearing capacity of the materials. Higher differences can cause damage to the substrate and the mortar. The state of stress caused by differential thermal expansion depends on E moduli, the temperature gradient (e.g. a sun heated surface), the geometry of the repair and the depth of the interface between the repair mortar and the substrate. The highest stress from the differential expansion will occur near the interface and will be proportional to E moduli of the materials. Mortar with lower E modulus than the substrate is preferred to avoid damage to the substrate. A special case has been reported for which no damage is expected despite the mortar with an acrylic binder has a much higher thermal expansion coefficient. This results from the higher viscoelasticity of the mortar. It represents an interesting case, but one that is also very different from the type of mortars discussed mainly in this paper [5]

4.2.4 Mortar should be slightly less mechanically resistant than the substrate

This requirement aims to protect the substrate assuming it is always more valuable than the repair itself. It is a relative precaution measure described commonly by the strength of materials. The basic single parameter criterion is that the tensile strength of mortar (or its bond strength) should be lower than the tensile strength of substrate. However, the failure mechanisms are more complex depending on a variety of factors including the deformation characteristics of the two bonded materials under loading. These requirements should be in balance with other performance criteria such as durability or physical and mechanical characteristics, e.g. material with a relatively high strength (compressive, tensile) can be repaired with a mortar with relatively high strength (but lower than the substrate) providing that the coefficient of thermal expansion of these two materials is not too different. It should be remembered that degraded materials have a low modulus of elasticity, as well as comparatively lower thermal dilation characteristics.

Most natural stones have relatively high strength parameters. The repair mortars therefore can be designed with much lower strength. Matching the strength parameters of the substrate is not required. However, strength related properties are key parameters in terms of performance behaviour of binders in relation to their composition and hardening processes. Therefore, they are important in terms of quality control and also in terms of compatibility assessment as described above.

4.2.5 Mortar should release the minimum amount of salts (preferably none)

Considering the long term problems associated with the presence of soluble salts, it is fundamental that no ions are added to the substrate with the repair materials. Hygroscopic salts are particularly dangerous and should be avoided or, at least, reduced to a minimum.

Typically, the water soluble anions content is not provided by the suppliers of proprietary repair mortars and so needs to be independently identified, if required, for the specific situation. Commercial products present only conformity with the associated standards. For example, the European standard on building limes (EN 459-1) limits the content of SO_3 to max. 2 % (wt.) for CL, DL, NHL and FL categories. Category HL can have SO_3 content up to 7 % (wt.) if it complies with the limits of volumetric stability tests. Ordinary Portland cements have SO_3 content around 3% (wt.). Recent papers from a RILEM TC provide initial information on the nature and relevance of salt test methods [42, 43].

4.3 Adequate service life

Technical requirements for the adequate service life are similar with those already mentioned above. The following points highlight the requirements related to the durability of repair.

4.4 Careful execution of the work including adequate curing conditions

The composition of the mortar is very important to ensure appropriate short and long term behaviour, however this behaviour is heavily linked with the application process. The fundamental aspects are mentioned in the design issues section above.

4.5 Mortar should be resistant to the expected environmental loads

A balance has to be found between the design of mortars, with the properties that will be able to withstand the exposure, and the risks of incompatibility resulting in damage to the substrate. The most typical reason for the loss of the original substrate is degradation associated with moisture in combination with cyclic loading (wetting and drying, freeze-thaw, temperature cycling, hygric and hydric expansion or materials, salt hygroscopicity and crystallisation, wind erosion). Therefore the parameters to design and assess for should be related to the expected mechanisms of deterioration. Attempts should be made to control the presence of moisture and to encouraging its evaporation.

4.6 Weathering and deterioration of the mortar should not lead to cracks

Mortar repair should preferably decay gradually across the area while maintaining a bond with the substrate. Brittle materials that are relatively strong and durable but fail to withstand loads and that degrade by formation of fissures and cracks should be avoided. They may be relatively well bonded to the substrate but the decay will continue along the cracks.

4.7 Consideration of a future treatment

The ability to repeat the repair action with no detriment to the original fabric should be considered at the initial stage when the mortar repair is being selected as the optimal method. It is easier to repair mortars that were designed to be sacrificial than excessively strong, permanent, repairs that have not performed according to the original plans. Hard mortars are difficult to remove, therefore softer sacrificial materials are always preferred. In this way the frequent request for “reversibility” can be partially fulfilled.

5 Final remarks

Mortar repair is a specialised technique that has been widely used in conservation practice in the past and the effectiveness of this treatment can be assessed today. There have been many failures but also some positive, successful repair cases. This experience has led more recently to a rehabilitated opinion about this repair method, in combination with the new understanding of performance and functional requirements. This paper has summarized this knowledge. In many circumstances it defines the need to measure material properties to guide the restorer’s choice. However, it deliberately has not gotten into quantitative evaluation criteria using those properties, as this would be beyond the scope of this paper. References have been given where possible, but in many cases more research is needed to deliver such quantitative criteria.

Compliance with Ethical Standards
The authors declare that they have no conflict of interest.

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Table 1: Guidelines related to mortar repair in relation to its appearance.

Mortar repairs of	Appearance / Appreciation	Colour and texture	Example
archaeological ruins in general	in general recognisable from the archaeological remains, no falsification	no strict limits, harmonious match in colour and texture in general	modelling of missing parts, protection of decayed and exposed elements
facades and architectural elements	unification with the repaired element / surroundings, reinstating its shape if desired by architectural style (surrounding architecture should be taken into account), but distinguishable after close observation	match in colour and texture in general	rendering architectural features, repair of degraded parts, improved protection of the remaining parts, figures 7, 8
ornaments, decorations and sculptures	typically not recognisable on the first look, but distinguishable after close observation, unified harmonious appearance	match in colour and texture, colour retouching of repair and surrounding material	restoration of decorative elements, repair of degraded parts, improved protection of the remaining parts, figure 9.

Table 2: Technical properties of mortar binder compositions versus classification of mortar according to the type of binder [**6**, **7**]. The relative scale for each specific technical property runs from 1 (low value) to 6 (high value).

	General binder type						
Property	Air lime	Natural hydraulic lime NHL 2, 3.5, 5	Pozzolan lime	Natural and Roman cements	Calcium silicate cements	Epoxy resins	Acrylics
Adhesion	3	3-5	3-4	4-6	5-6	4-6	3-6
Strength (comp, flexural, tensile)	2	2-5	2-4	4-6	5-6	4-6	3-6
E-modulus	1	1-4	1-3	4-6	5-6	4-6	3-6
Water penetration resistance	3	3-4	3-4	5-6	5-6	5-6	5-6
Freeze-thaw resistance	2	3-4	3-4	4-6	4-6	5-6	5-6
Thermal dilatation	1	1	1	1	1	5-6	5-6
Vapour transmission	5	4-5	3-4	3-5	2-4	1-3	1-3
Aesthetic	Depends on specific requirements						

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Table 3. Selected commercial stone repair mortars and their properties published in technical documentation.

product name	ref.	binder	R_t	R_f	R_c	E	α	η	w	p	μ	cc
			MPa	MPa	MPa	GPa	°K^{-1} 10^{-6}	%	wt.-%	vol.-%	-	kg.m^{-2}.h$^{-½}$
M70 Sandstone	[27]	mineral based	1.0–2.0	2.9–3.7	12–15	17–18	62–76	0.45 – 0.54	~ 14	34–36	-	-
M100 Terracotta/brick	[28]	mineral based	1.0	4.3	21–26	1.5–11	1.8–5.4	-	-	4–17	-	-
M160 Granite	[29]	cementitious, mineral based	4.8–7.0	4.1–4.8	25–37	19–20	-	-	1.8–4.5	-	-	-
Lithomex St.One	[30]	natural hydraulic lime	2.4	-	7	8	-	-	-	-	9.4	10.3
Petra C	[31]	cement, mineral based	-	-	20–30	-	-	-	-	-	-	-
Petra E	[32]	epoxy resin	-	-	35–65*	-	-		0.9–5.5	-	-	-
Restoration mortar soft	[33]	mineral based	0.5^b	-	8	9	-	-	-	-	-	-
Restoration mortar CF (cement free)	[34]	mineral based	-	1.2	3	3.5	-	-	-	-	-	-
Bridevaux Soft sandstone	[35]	mineral based, lime, trass cement, additives (<5%)	-	1.9	5	1	9.1	-	17	40^t	< 15	12.4
Bridevaux Hard sandstone	[36]	mineral based, lime, trass and white cement, additives (<5%)	-	2.1-4.0	8–11	4-7	5–8	-	-	40-45^t	-	12.4

R_t – tensile strength, R_f – flexural strength, ^{b} – bond; R_c – compressive strength, * @72 hours, E – modulus of elasticity, α – linear coefficient of thermal expansion, η –coefficient of hydraulic expansion, w – water absorption; p – total open porosity, ^{t} – total porosity; μ - water vapour resistance factor, cc – capillary water absorption coefficient.

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Figure 1: Advanced deterioration of a 19th century sandstone ashlar masonry façade in Bearsden. Scotland.

Figure 2: Example of mortar application (light parts) as a mortar repair of deteriorated stone units in Glasgow. Scotland.

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Figure 3: Mortar used to repair deteriorated stone parts and detailing of the main entrance portal of the cathedral in Évora. Portugal.

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Figure 10: Stone repair (right side). Texture is adapted to the original substrate finishing technique.

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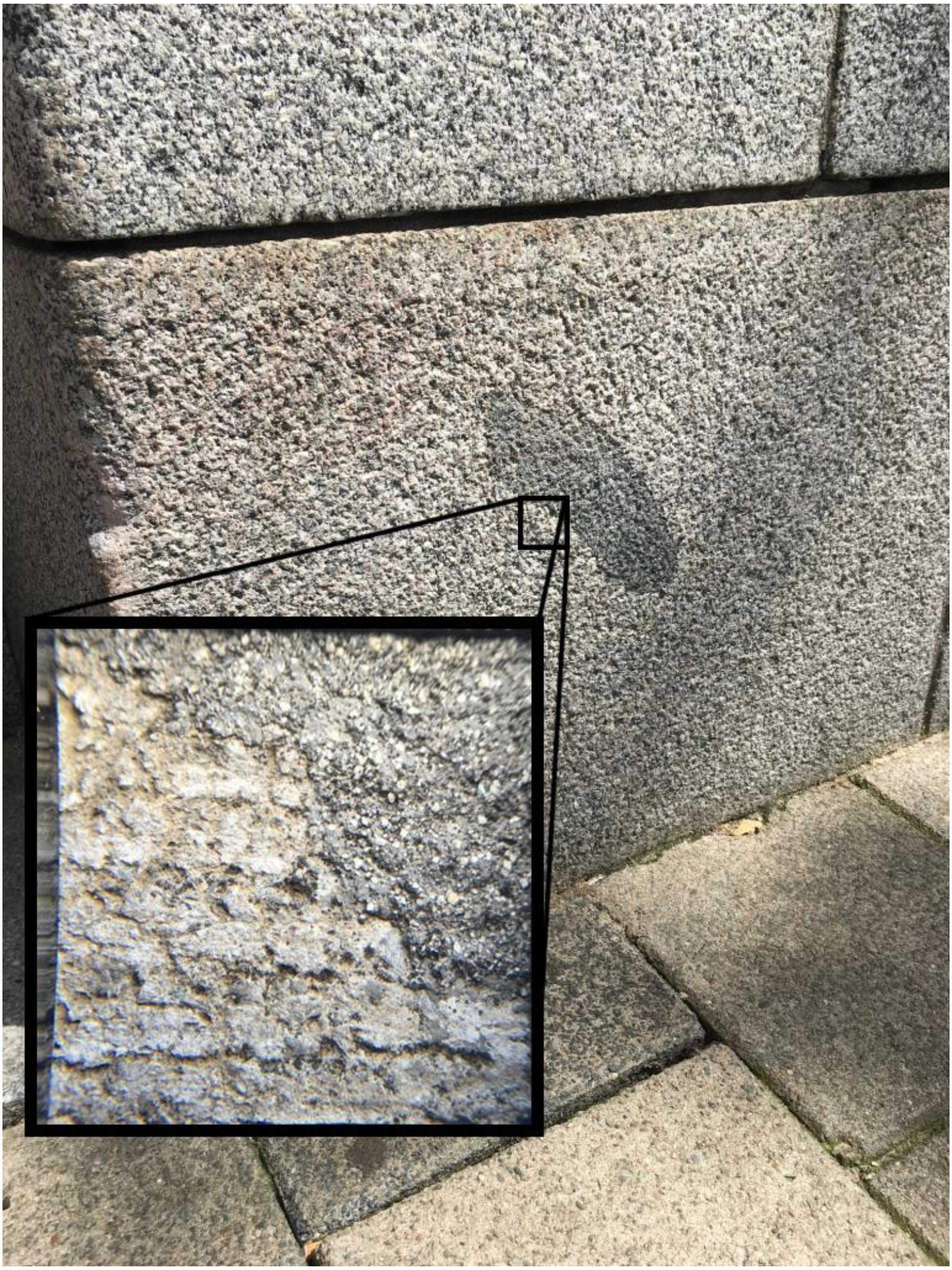

Figure 11: Stone repair with detail of a visually sound bond. Amsterdam.

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Figure 12: Stone repair with detail of a failing bond, due to shrinkage of the repair mortar. Amsterdam.